CHAPTER - 2

DEVELOPMENTS OF DIFFERENT THEORETICAL PREDICTIONS

The theoretical value of the differential cross section in which all the four elastic processes of scattering combine coherently is expressed in the general form by

$$\frac{d\sigma}{d\Omega} = \left| a^{(NT)} + a^{(R)} + a^{(D)} + a^{(NR)} \right|^2 \quad \ldots (2.1)$$

where the superscripts (NT), (R), (D) and (NR) refer to nuclear Thomson, Rayleigh, Delbruck and nuclear resonance scattering amplitudes respectively. Excepting nuclear Thomson scattering amplitude all other scattering amplitudes are complex e.g. $a^{(R)} = a_1^{(R)} + i\, a_2^{(R)}$ where the subscripts 1 and 2 refer to the real and imaginary parts respectively.

While using these amplitudes to calculate the differential cross sections, the photon polarization is taken into account. For linearly polarized photons, these amplitudes are expressed as components parallel (a_{11}) and

perpendicular ($a_\perp$) to the plane of scattering. The amplitudes for scattering of circularly polarised photons with no change of polarisation are denoted by a_{NSF} and with change of polarisation by a_{SF}. The scattering amplitudes for circularly polarised photons are related to the amplitudes for linear polarisation by

$$a_{S.F.} = \frac{1}{2}(a_{\parallel} - a_{\perp}), \quad a_{NSF} = (a_{\parallel} + a_{\perp})/2 \quad \ldots (2.2)$$

Since all the elastic scattering processes may act simultaneously they interfere with each other and it is necessary to know the relative phases of these scattering amplitudes in the sum (2.1). These relative phases have been reliably determined by Papatzacos[20].

2.1 Nuclear Thomson amplitudes

The nuclear Thomson scattering amplitude is well known for a given scattering angle θ and target atomic number Z. The amplitudes are expressed as components perpendicular and parallel to the plane of scattering in units of classical electron radius by

$$\sigma_{\perp}^{(NT)} = \frac{Z^2 m}{M} \quad \text{and} \quad \sigma_{\parallel}^{(NT)} = \frac{Z^2 m}{M}\cos\theta$$

... (2.1.1)

where m/M is the ratio of electron rest mass to the atomic mass and $m/M \sim 1/1823\ A$ where A is the atomic weight.

2.2 Rayleigh scattering amplitudes

The first attempt to calculate Rayleigh scattering amplitude was made by Franz[21] in 1933 and was improved upon by Moon[22] in 1950 and by Bethe[23] in 1952. His method widely known as the Form Factor Approximation is still being used with modifications. The differential elastic scattering cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}(1+\cos\theta)\left|F(q,Z)\right|^2$$

... (2.2.1)

where $F(q,Z)$ is the form factor for a given momentum transfer q, Z is the atomic number and r_0 is the classical electron radius. The form factor is expressed[24] as the matrix element

$$F(q,Z) = \sum_{n=1}^{Z} \langle \psi_0 | \exp(i\mathbf{q}\cdot\mathbf{r}_n) | \psi_0 \rangle \quad \ldots (2.2.2)$$

where ψ_0 is the ground state wave function of the atom, $\mathbf{r}_n$ is the radius vector from the nucleus to the n^{th} electron. The atomic form factor is also expressed[25] as

$$F(q,Z) = \int \rho(r) \exp(i\mathbf{q}\cdot\mathbf{r})\, d^3r \quad \ldots (2.2.3)$$

where $\rho(r)$ is the total electron density at r. For a spherically symmetric atom the angular integrations are performed[26] resulting in

$$F(q,Z) = 4\pi \int_0^\infty \rho(r) \frac{\sin qr}{qr} d^3r \qquad \ldots (2.2.4)$$

There have been many calculations and tabulations of atomic form factors, emphasis being given to the use of different wave functions. An excellent summary of these calculations is given by Hubbell[9].

In his paper on form factor Frans[21] proposed a correction to the form factor. Later, Brown and Mayers[4] gave a semiempirical formula for correcting the form factor approximation. These are known as modified form factors. The modified form factor g(q,z) is given by

$$g(q,Z) = 4\pi \int_0^\infty \rho(r) \frac{\sin qr}{qr} \frac{1}{1-\epsilon-V(r)} d^3r. \qquad \ldots (2.2.5)$$

where $E=1-\epsilon$ is the energy of the electron and $V(r)$ is the atomic potential.

Tabulation of the non-relativistic atomic form factors (HFIF) $F(q,Z)$ for $Z = 1$ to 100 and $q = .005 A^{Q-1}$ to $10^{2} A^{-1}$ have been compiled by Hubbell[9]. These tables are constructed from the theoretical data of Brown[27,28], Cromer and Mann[29].

The recent addition is the tabulation of relativistic form factors (RFF) compiled by Hubbell[10]. It includes $F(q,Z)$ values for q from .01 to $10^{2} A^{-1}$ for elements $Z = 1$ to 100 from different researchers, viz., Doyle and Turner[30], Cromer and Weber[31] and Øverbø[32].

A method for evaluating transition amplitudes for bound electrons in second order in the effect of the radiation field was outlined by G.E.Brown and his co-workers[1-4] in 1954-57. They described a method for solving the Dirac equation which describes the wave function including not only a small perturbing term but a large static potential. The effect of electron binding in the calculation of form factors were taken into account. During 1954-57 Brown and his co-workers published Rayleigh scattering amplitudes for photons scattered by K-shell electrons of mercury atoms at photon energies of 0.164,

0.327, 0.654 and 1.308 MeV using Coulomb potential. Later, Cornille and Chapdelaine[33] following Brown's procedure calculated Rayleigh scattering amplitudes for the K-shell electrons of mercury atoms for photon energy of 2.62 MeV.

It was almost a decade since Brown and his co-workers published results of Rayleigh amplitudes, Johnson et al[34,35,6] extended Brown's procedure and published results of Rayleigh scattering amplitudes using D.H.F.S wave functions rather than the Coulomb wave functions as used by Brown. Johnson et al also extended their calculations to L and M shell electrons in certain cases. Johnson and Cheng[5] have published results of Rayleigh scattering amplitudes at photon energies of 0.145, 0.279, 0.412, 0.662 and 0.889 MeV for lead atoms and at photon energies of 0.279 and 0.662 MeV for Z = 30, 42, 56, 60 and 73.

The most recent and exhaustive calculations of Rayleigh scattering amplitudes from numerical solution of second order S-matrix have been done by Kissel and Pratt[6,7]. They have used potential and wave functions resulting from DHFS type self-consistent calculations. Kissel and Pratt have used Kohn-Sham exchange model rather than the Slater exchange model as used by Johnson and Cheng. Kissel and Pratt have reported[6,7] Rayleigh

scattering amplitudes for the following atoms Z = 2, 13, 30, 42, 47, 50, 62, 73, 74, 79, 80, 82 and 92 for a wide range of photon energies starting from a few KeV upto 2.754 MeV for different inner shell electrons.

There is one more recent calculation of Rayleigh scattering amplitude made by Florescu and Gavrila[11]. They have evaluated matrix element for Rayleigh scattering amplitudes by K-shell electrons in the high energy limit and finite momentum transfer. The atomic field was assumed to be Coulomb in form. The integration in the momentum space was carried out by use of non-relativistic Green's function. They have published the results of scattering amplitudes H as a function of αZm where α is the fine structure constant. The Rayleigh amplitudes are given by

$$a_{\perp}^{(R)} = 2H \quad \text{and} \quad a_{\parallel}^{(R)} = 2H\cos\theta$$

... (2.2.6)

The values of H are available for Z = 1,6, 13, 29, 42, 50, 60, 73, 80, 82 and 92 for values of $q/\alpha Zm$ from 0 to 15.

Table 1 Comparison of differential elastic cross sections (in unit of 10^{-26} cm^2/sr) including Rayleigh and Thomson scattering amplitudes using Rayleigh amplitudes of Kissel and Pratt and form factors.

ENERGY	ATOMIC NUMBER	θ(°)	q in au		R.P K L M	O.F.F. K L M	R.P. K L M N	O.F.F. K L M N	H.F.F. K L M N	H.O.(RHF) TOTAL ATOM
50.54 KeV	82	0.10	2.031	-04	5646.00	6235.63	27286.7	28539.7	27633.1	
		1.00	2.031	-03	5661.60	6229.00	27191.4	28504.99	27539.4	52702.6
		10.00	2.029	-02	5244.16	5799.62	19509.0	20804.87	19843.4	22562.6
		30.00	6.022	-02	2962.27	3372.62	3534.5	3970.17	3601.2	4161.67
		60.00	1.163	-01	658.63	850.86	603.16	866.19	766.8	867.61
		90.00	1.646	-01	186.41	263.92	224.19	306.23	258.9	315.68
		120.00	2.015	-01	130.28	199.67	144.22	214.58	173.6	218.59
		150.00	2.248	-01	136.37	223.30	142.38	228.16	180.6	230.89
		180.00	2.327	-01	142.29	239.65	145.16	241.33	182.4	244.32

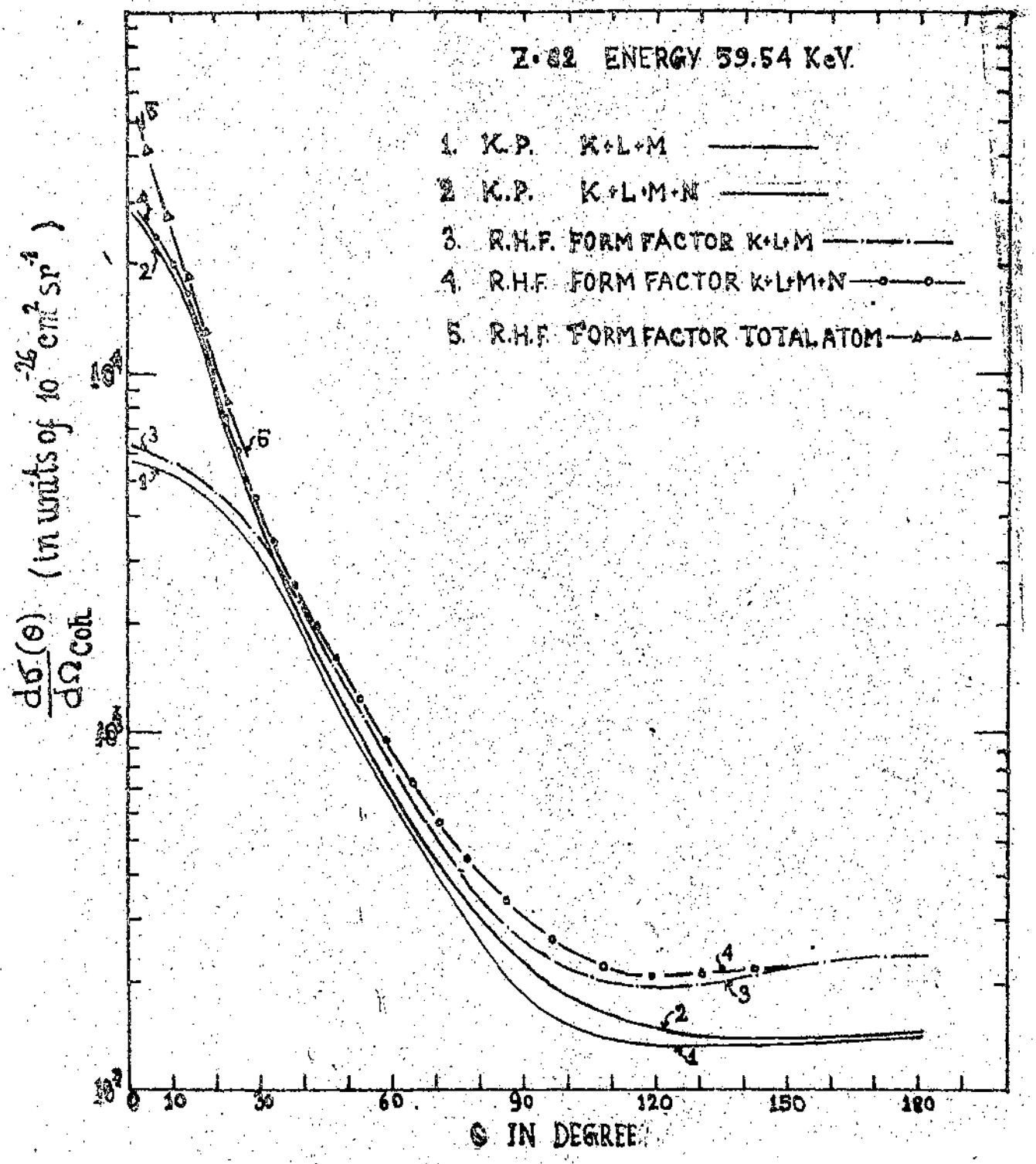
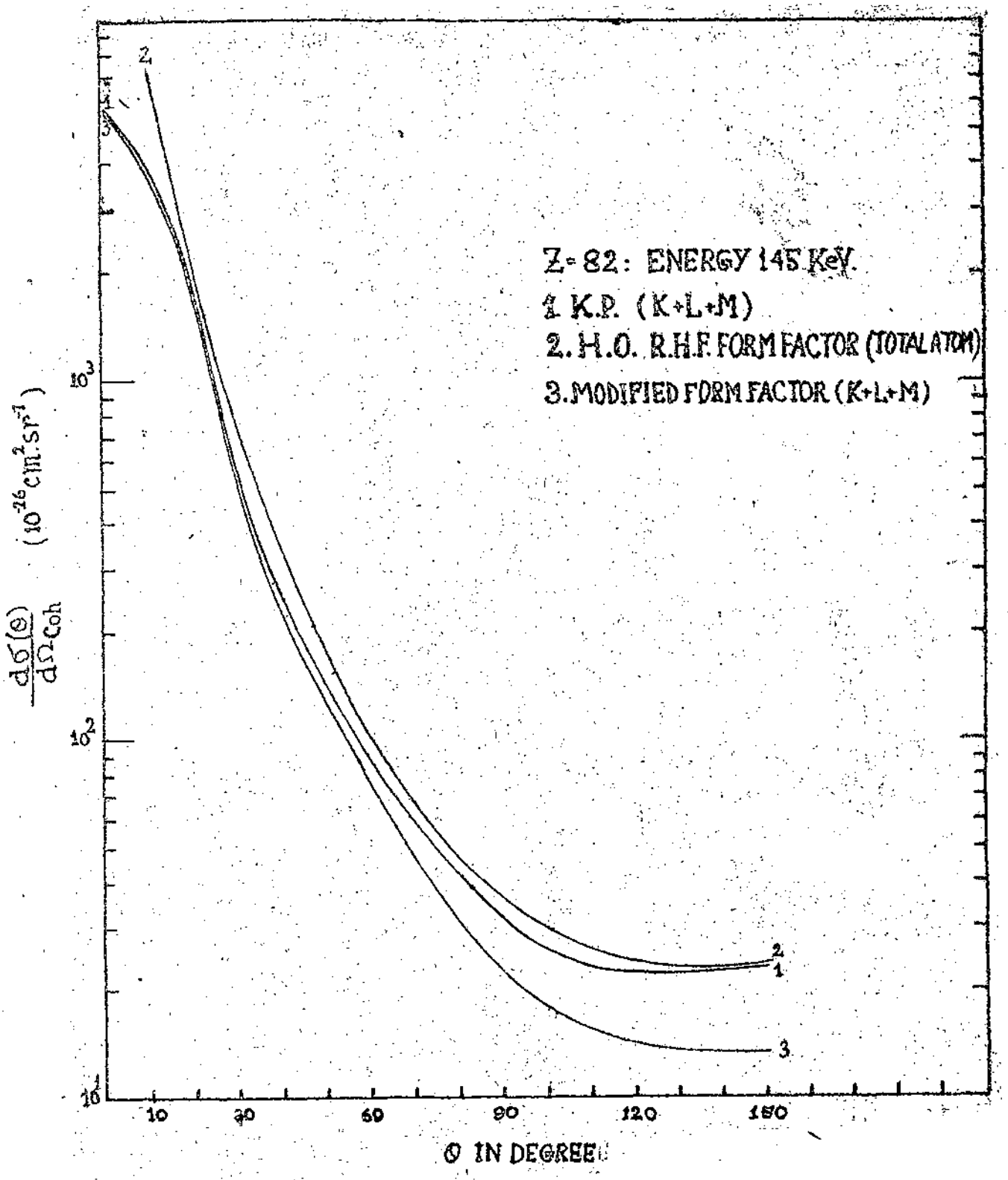

Z=62 ENERGY 59.54 KeV.
1. K.P. K+L+M
2 K.P. K+L+M+N
3. R.H.F. FORM FACTOR K+L+M
4. R.H.F. FORM FACTOR K+L+M+N
5. R.H.F. FORM FACTOR TOTAL ATOM
dσ(θ)/dΩ Coh (in units of 10^-26 cm^2 sr^-1)
θ IN DEGREE
0
10
30
60
90
120
150
180

Fig. 1.

Table 2 Comparison of differential elastic cross section (in units of 10^{26} Cm/Sr) including Rayleigh and Thomson amplitudes.

ENERGY	ATOMIC NUMBER	θ(°)	q in mc	K.P. K L M x 10^{-26}	F.G. x 10^{-26}	H.O(RHF) TOTAL ATOM x 10^{-26}	J.O. K L M x 10^{-26}	K.P. x 10^{-26}	K.P. K real only x 10^{-26}	HFF K L M x 10^{-26}
145 KeV	92	1.00	4.964 -03	5949.10		47627.96		39.79	29.72	5839.61
		10.00	4.959 -02	4195.08	23.178	6899.05		38.92	29.13	4106.47
		30.00	1.472 -01	564.78	19.58	745.00	566.44	32.78	24.66	536.61
		60.00	2.845 -01	90.67	12.07	102.39	90.75	20.25	15.71	80.10
		90.00	4.023 -01	32.57	7.962	37.70	33.19	14.30	10.90	24.94
		120.00	4.930 -01	23.45	3.258	24.37	23.95	16.13	12.30	14.80
		150.00	5.493 -01	23.68	10.14	24.31	24.16	20.41	15.95	13.77


Z= 82: ENERGY 145 KeV.
1 K.P. (K+L+M)
2. H.O. R.H.F. FORM FACTOR (TOTAL ATOM)
3. MODIFIED FORM FACTOR (K+L+M)
$\frac{d\sigma(\theta)}{d\Omega_{Coh}}$ (10^{-26} cm^2.sr^{-1})
10^3
10^2
10
10
30
60
90
120
150
θ IN DEGREES
1
2
3

Fig, 2.

Table 3 Comparison of the sum of squared amplitudes (in units of classical electron radii)

ENERGY	ATOMIC NUMBER	Q(°)	q in mc	K.P. K L	J.C. K L	FORM FACTOR K L	MODIFIED FORM FACTOR K L	H.O. TOTAL ATOM FORM FACTOR	P.C. K	K.P. K
411.3 KeV	82	0.10	1.403 -03	90.28		99.99	88.21	6652.0	2.024	3.307
		1.00	1.406 -02	89.81		99.50	87.75	3991.9	2.016	3.304
		10.00	1.404 -01	54.98		62.38	53.58	117.5	1.067	3.076
		30.00	4.171 -01	5.963	4.000	5.630	3.951	7.375	1.650	1.734
		60.00	8.060 -01	0.4522	0.4334	0.0300	0.4379	0.8566	0.4367	0.4533
		90.00	1.130 00	0.1836	0.1044	0.3145	0.1404	0.3307	0.1171	0.1673
		120.00	1.393 00	0.1460	0.1468	0.2141	0.0506	0.2234	0.0602	0.1262
		150.00	1.556 00	0.1374	0.1382	0.2040	0.0679	0.2212	0.0474	0.1171
		180.00	1.611 00	0.1349		0.2047	0.0652	0.2231	0.0449	0.1146

Table 4 Comparison of differential elastic cross section (in units of 10^{-26} cm^2/sr) including Rayleigh and Thomson amplitudes.

ENERGY	ATOMIC NUMBER	θ(°)	q in cm	K.F. K L M	F.F. K	H.O.(HFF) TOTAL, ATOM	M.F.F. K L M	O.F.F. K L M	K.F. K	HFF K
				x 10^{-26}	x 10^{-26}	x 10^{-26}	x 10^{-26}	x 10^{-26}	x 10^{-26}	x 10^{-26}
1.3325 MeV	82	1.00	4.55 -02	4306.25	23.54	6159.26	4390.04		23.98	23.03
		10.00	4.54 -01	34.566	14.12	50.83	54.0136		14.11	14.33
		30.00	1.34 00	1.0257	0.3774	2.998	0.9099	2.9456	0.3115	0.9459
		45.00	1.99 00	0.1069	0.09364	0.6227	0.3547	0.6068		
		60.00	2.69 00	0.02612	0.01529	0.1305	0.02614	0.1549	0.01343	
		75.00	3.17 00	0.01335	0.004166		0.007311	0.05703		
		90.00	3.63 00	0.008959	0.002041	0.0324	0.003556	0.02735	0.006996	
		120.00	4.51 00	0.007363	0.001715	0.01359	0.002243	0.01543	0.006409	
		150.00	5.03 00	0.008117	0.002308	0.01587	0.002603	0.01459	0.006326	

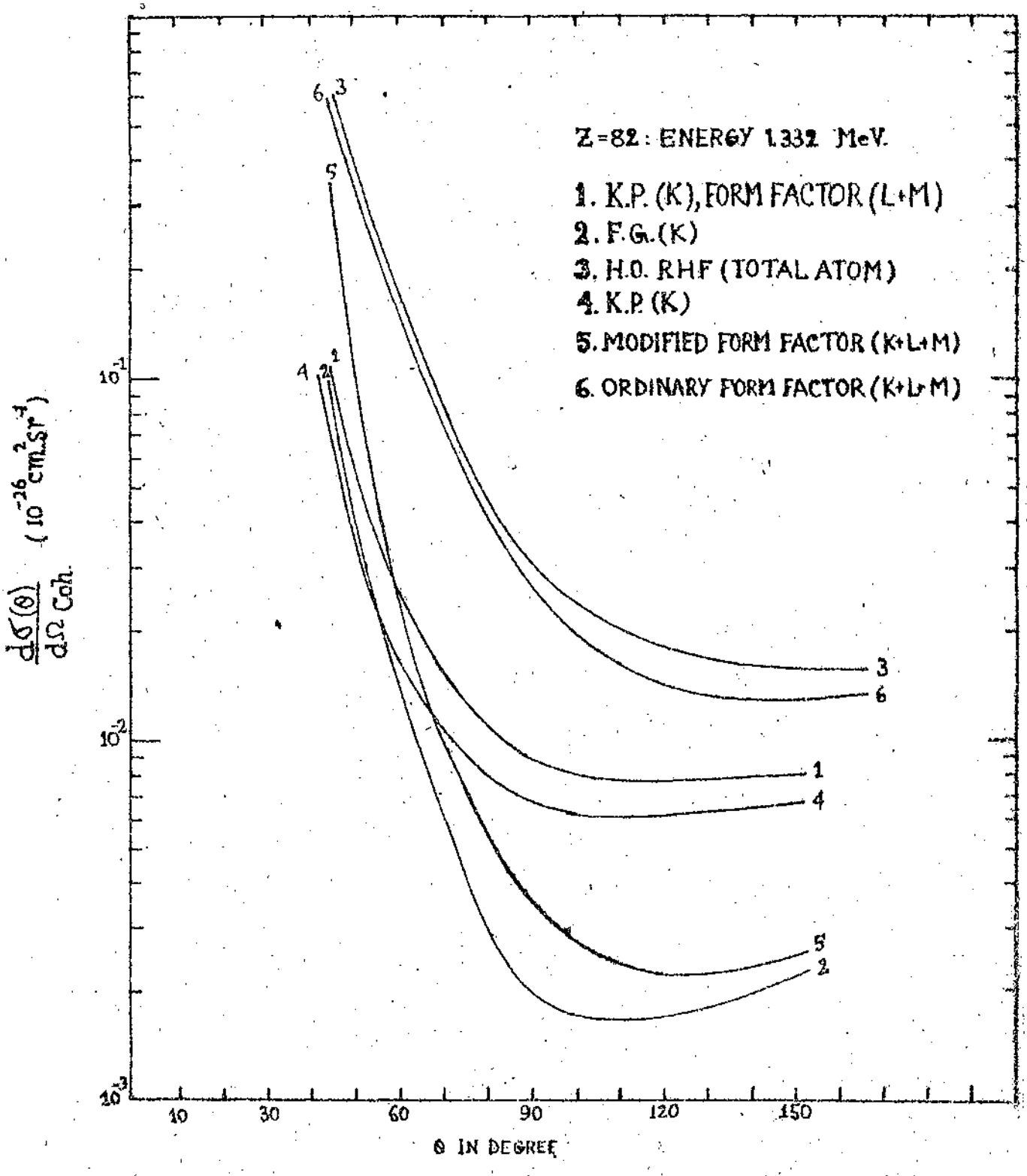

Z=82 : ENERGY 1.332 MeV.
1. K.P. (K), FORM FACTOR (L+M)
2. F.G. (K)
3. H.O. RHF (TOTAL ATOM)
4. K.P. (K)
5. MODIFIED FORM FACTOR (K+L+M)
6. ORDINARY FORM FACTOR (K+L+M)
$\frac{d\sigma(\theta)}{d\Omega}$ Coh. (10^{-26} cm^2.Sr^{-1})
10^{-1}
10^{-2}
10^{-3}
10
30
60
90
120
150
θ IN DEGREE

Fig. 3.

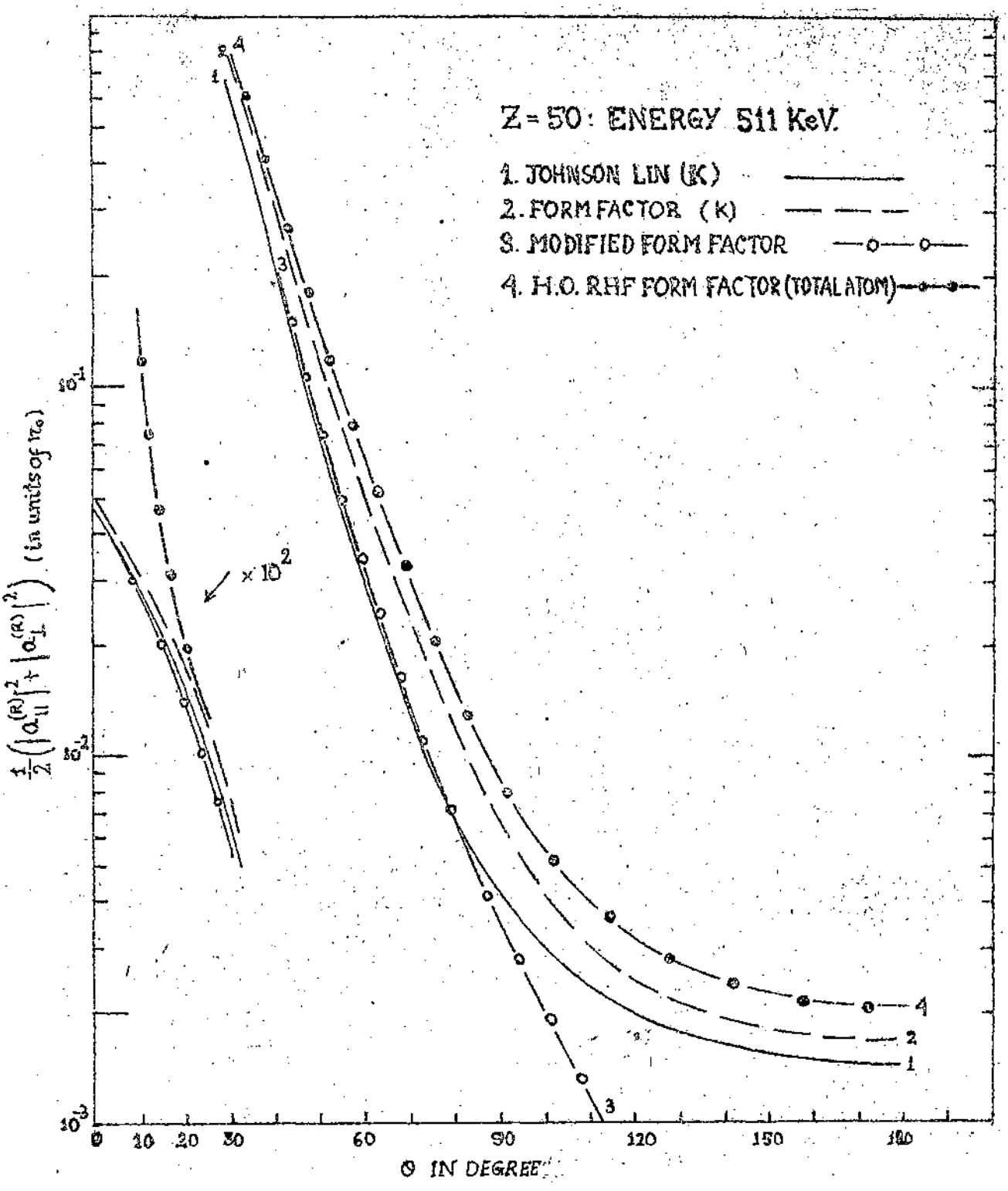

Z = 50 : ENERGY 511 KeV.
1. JOHNSON LIN (K)
2. FORM FACTOR (K)
3. MODIFIED FORM FACTOR
4. H.O. RHF FORM FACTOR (TOTAL ATOM)
$\frac{1}{2}\left(|a_{11}^{(R)}|^2 + |a_{\perp}^{(R)}|^2\right)$ (in units of r_0)
$\times 10^2$
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
60
90
120
150
180
θ IN DEGREE

Fig. 4.

Table 5 Comparison of the sum of the squared Rayleigh scattering amplitudes (in classical electron radii) for K-shell electrons by Brown et al, Kissel and Pratt, Florescu and Gavrilla and total atom relativistic form factors due to Øverbø and Hubbell are compared.

ENERGY	ATOMIC NUMBER	Q(°)	q in me	B.M. K-shell	K.P. K-shell	F.G. K-shell	H.O. (R.H.F.) TOTAL ATOM
1.303 MeV	80	0.00		2.889	3.093	2.9680	
		15.00	6.66 -01	0.9411		0.9695	1.783
		30.00	1.32 00	0.3600	0.0697	0.09622	0.3351
		45.00	1.96 00	0.006766		0.008244	0.06309
		60.00	2.56 00	0.00111	0.00121	0.007978	0.01617
		90.00	3.62 00	0.000609	0.000355	0.00000269	0.002197
		120.00	4.43 00	0.000483	0.000204		
		150.00	4.90 00	0.000477	0.000147		
		180.00	5.12 00	0.000450	0.000133		

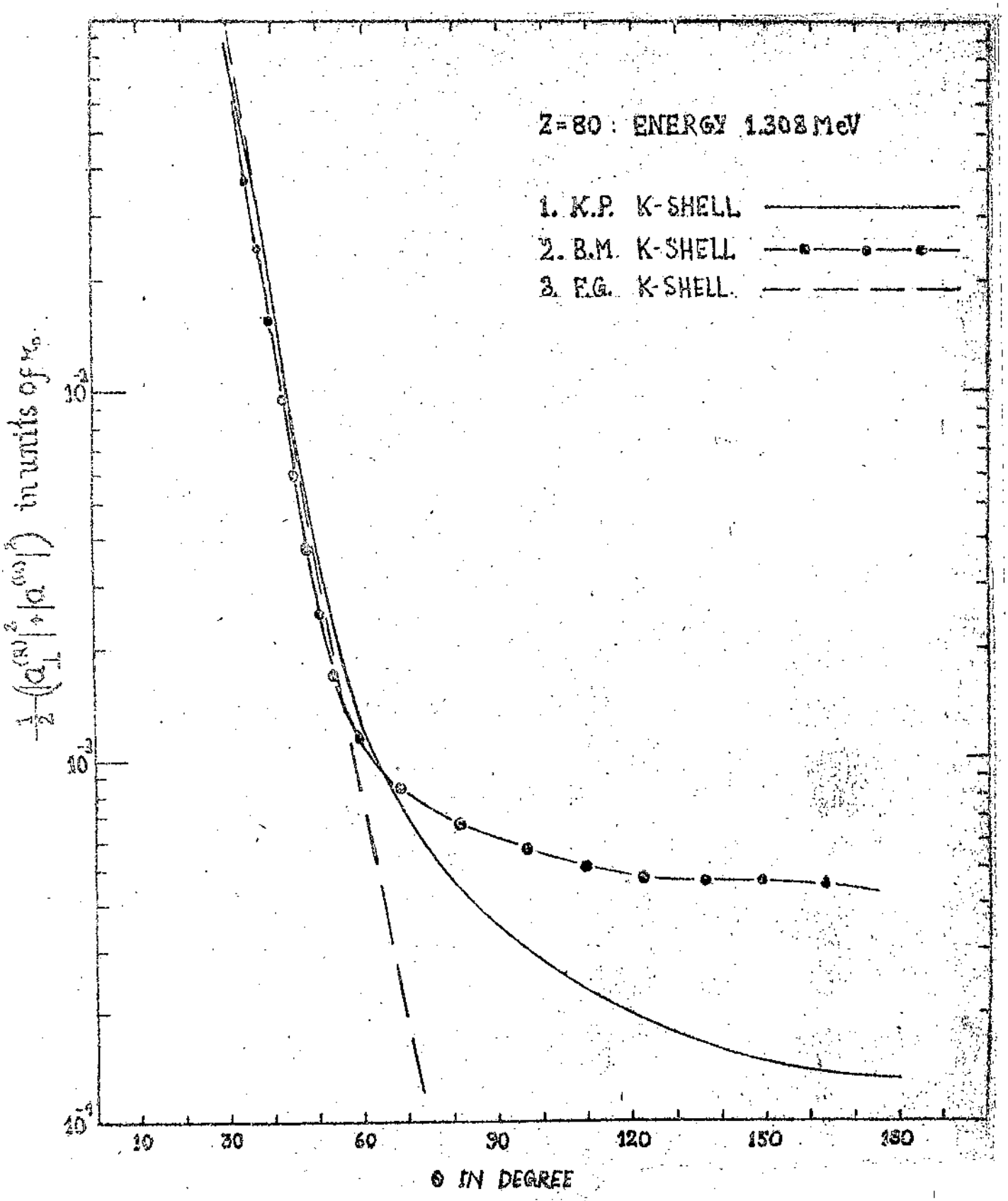

Z=80 : ENERGY 1.308 MeV
1. K.P. K-SHELL
2. B.M. K-SHELL
3. F.G. K-SHELL
$\frac{1}{2}\left(|a_{\perp}^{(s)}|^2 + |a^{(s)}|^2\right)$ in units of r_0^2
10^{-2}
10^{-3}
10^{-4}
10
30
60
90
120
150
180
θ IN DEGREE

Fig. 5.

Table 6 Comparison of the sum of squared scattering amplitudes (in classical electron radii) electrons by Johnson & Lin, Florescu & Cavrilla, Kissel & Pratt, K-shell modified form factor denoted by KMF, K-shell ordinary form factors denoted by KFF and total atom relativistic Hartree Fock form factors due to /Verb/ and Hubbell.

ENERGY	ATOMIC NUMBER	Q(°)	q in ao	J.L. K	K.C. E.	K.P. K	K.F.F.	K.M.F.	H.O.(RHF) TOTAL ATOM
511 KeV	50	0.00		3.606	3.535	3.614	3.9992	3.5573	
		10.00	1.74 -01	2.855	2.798		3.183	2.797	16.35
		20.00	3.46 -01	1.5063	1.485		1.738	1.466	1.906
		30.00	5.17 -01	0.6150	0.6115		0.7636	0.6068	0.7678
		40.00	6.84 -01	0.2245	0.2240		0.3054	0.2241	0.3527
		60.00	9.99 -01	0.03075	0.02943	.03071	0.05097	0.03139	0.06422
		90.00	1.41 00	0.004276	0.002478		0.006664	0.002314	0.003584
		120.00	1.73 00	0.002073	0.002042	.002073	0.002437	0.0007242	0.003243
		180.00	1.99 00	0.001415	0.001376	.001408	0.001668	0.0001782	0.002148

Table 7 Comparison of the sum of squared Rayleigh scattering amplitudes (in classical electron radii) for K-shell electrons by Johnson and Lin, Florescu and Savrilla, Kissel and Pratt and total atom R.H.P. form factors due to Øverbø and Hubbell and non-relativistic form factors due to Cromer et al are compared.

ENERGY	ATOMIC NUMBER	θ(°)	q in mc	F.C. K	J.L. K	K.P. K	O.H.(RHF) TOTAL ATOM	CROMER (RHF) TOTAL ATOM
40.80 KeV	18	0.00		5.964	4.0442	4.0433		
		30.00	4.14 -02	2.618	2.9364		7.611	7.566
		60.00	7.99 -02	1.263	1.3186	1.5160	1.186	1.2169
		90.00	1.15 -01	0.5271	0.6089		0.5514	0.5497
		120.00	1.53 -01	0.1481	0.4654	0.4654	0.4383	0.4471
		150.00	1.54 -01	0.4525	0.4712		0.4513	0.4607
		180.00	1.59 -01	0.4618	0.4814	0.4814	0.4610	0.4688

Table 8 Comparison of the sum of squared Rayleigh scattering amplitudes (in classical electron radii) for K-shell electrons by Kissel and Pratt, Florescu and Gavrila and total atom form factors by Hubbell and /verb/ are compared.

ENERGY	ATOMIC NUMBER	θ(°)	q in mc	F.G. K-shell	H.O. (R.H.F) TOTAL ATOM	K.P. K-shell
145.4 KeV	13	0.00				5.974 00
		5.00	2.43 -02	5.633 00	30.92 00	3.672 00
		10.00	4.96 -02	3.072 00	5.954 00	2.924 00
		20.00	9.88 -02	1.436 00	1.306 00	1.320 00
		30.00	1.47 -01	5.312- 01	6.135 -01	4.656 -01
		45.00	2.17 -01	1.044 -01	1.055 -01	8.753 -02
		60.00	2.84 -01	2.230 -02	2.235 -02	1.863 -02
		90.00	4.01 -01	2.228 -03	2.361 -03	1.863 -03
		120.00	4.92 -01	6.770 -04	7.447 -04	6.164 -04
		150.00	5.49 -01	4.290 -04	4.901 -04	4.068 -04

Table 2 Comparison of the sum of squared Rayleigh amplitudes (in classical electron radii) for K-shell electron by Kissel and Pratt, Florescu and Gavrila and total atom relativistic form factors by Hubbell and /verb/ are compared.

ENERGY	ARGUIC NUMBER	Q(°)	q in mc	F.G. K-shell	H.O. (R.H.F) TOTAL ATOM	K.P. K-Shell
279.2 KeV	13	0.00				3.967 00
		5.00	4.766 -02	3.027 00	5.727 00	3.013 00
		10.00	9.520 -02	1.590 00	1.449 00	1.473 00
		20.00	1.897 -01	2.328 -01	2.358 -01	2.004 -01
		30.00	2.828 -01	3.104 -02	3.317 -02	2.690 -03
		45.00	4.181 -01	2.499 -03	2.775 -03	2.058 -03
		60.00	5.459 -01	3.132 -04	3.639 -04	2.636 -04
		90.00	7.725 -01	1.715 -05	2.309 -05	1.702 -05
		120.00	9.462 -01	3.713 -06	6.434 -06	5.144 -06
		150.00	1.055 00	2.439 -06	3.841 -06	3.236 -06

Comparisons of different calculations of Rayleigh scattering amplitudes available in literature are made with the help of some tables 1-9 and plots (Figs. 1-5), covering low, medium and high Z atoms as a function of energy and scattering angles.

2.3 Delbruck scattering amplitudes

The first theoretical work on Delbruck scattering was done by Kemmer[36] in 1937 and was restricted to photon energies $w \ll m$. At the same time in 1937 Akhiezer and Pomeranchuk[37] worked on high energy cases. They pointed out that the Delbruck amplitudes are proportional to e^4 though immediately after the Delbruck effect was proposed Oppenheimer[38] suggested that the transition probability of Delbruck scattering was of the order of $(\alpha Z)^4$. Akhiezer and Pomeranchuk[37] obtained same type of expressions as Kemmer's and obtained results for $m \leqslant q \leqslant w$. Akhiezer, Pomeranchuk and Kemmer missed the imaginary part of Delbruck amplitudes which dominates at high photon energies. The later calculations of Delbruck amplitudes were approached by two different ways. It was related either to pair production or to vacuum polarization. Jost et al[39] showed the relationship between Delbruck scattering and pair production from the unitarity of S-matrix and calculated

Delbruck amplitudes restricted to imaginary parts and to the forward direction only.

Rohrlich and Gluckstern[40] used dispersion relation to obtain real part of the Delbruck amplitudes with the help of the value of σ_{tot} calculated by Jost et al[39]. They checked the formulae so obtained with direct calculation of real and imaginary parts of Delbruck amplitudes from the diagonal S-matrix element. They used the Dyuman-Dyson formulation of quantum electrodynamics for the first time in calculating these amplitudes.

At the same time Bethe and Rohrlich[41] calculated Delbruck amplitudes in the high energy limit starting from optical theorem and ignoring photon polarization in the process.

An important work was done by Kessler[42] in 1960, generalising a method for computing non-diagonal matrix elements of S^4 from S^2. He obtained imaginary parts of the amplitudes parallel and perpendicular to the plane of scattering for arbitrary values of scattering angles as a five fold integrals. Integrations were performed for photon energy of 2.64 MeV and at scattering angle 90^0. Jarnik[43] extended Kessler's calculation to photon energy of 6.14 MeV upto scattering angle 180^0. Bhabha and Shoppy[13] used the formula derived by Kessler to

calculate the imaginary parts of the amplitude for a wide range of photon energies from 1 to 20 MeV and scattering angles upto 120^0. They obtained real parts in the form of six fold integrals with the help of fixed angle disperaion relation.

Recently Papatzacos and Mork[12] have calculated Delbruck amplitudes for a wide range of photon energies w varying from $w \leqslant 1$ MeV to several GeV from fourth order vacuum polarisation tensor using Fyuman technique in the lowest order Born approximation. Gauge invariance was applied to write the amplitudes. The integrals were reduced to four fold integrals by analytic integrations. The other integrals were calculated numerically. They have published results which differ from those obtained by Kholtsky and Sheppy[13] in real part of the amplitudes.

Between the work of Kholtsky and Sheppy on the one hand and that of Papatzacos and Mork on the other, Constentinl et al[44] derived formulae for Delbruck amplitude in the form of three fold integrals, the integrands containing many dilogarithm functions for the real part of the amplitudes. In 1978 De. De. Follis et al[45] manipulated the formulae obtained earlier and simple expressions were obtained in the form of a sum of two fold and three fold integrals containing rational, irrational and logarithm

functions. They have published results at 10.83 MeV photon energy and scattering angles from 50° - 150°. Their results agree with Papatzacos and Norke' result on the real part of the amplitudes compared to those obtained by Zhlotsky and Sheppy. In 1976 Barnoy and Kahane[46] calculated imaginary parts of Delbruck amplitudes following the work of Constantini for photon energies ranging from 1.33 MeV to 20 MeV and for scattering angles from 0° to 180°.